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Oster

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(54) **APPARATUS FOR MANIPULATING MAGNETIC FIELDS**

(75) Inventor: **Eugene L. Oster**, Los Gatos, CA (US)

(73) Assignee: **Oster Magnetics, Inc.**, San Jose, CA (US)

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(2), (4) Date: **Oct. 14, 2003**

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(51) **Int. Cl.**[7] **C23C 14/00**; C25B 11/00; H01F 1/00; H01F 5/00

(52) **U.S. Cl.** **335/296**; 335/297; 335/306; 204/298.16; 204/298.37

(58) **Field of Search** 335/210–214, 335/296–306; 156/345.42, 345.46, 345.49; 204/298.16–298.22, 298.37

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,668,365 A	5/1987	Foster et al.	
5,089,442 A	2/1992	Olmer	
5,527,394 A	6/1996	Heinrich et al.	
5,718,795 A	2/1998	Plavidal et al.	
6,015,476 A	1/2000	Schlueter et al.	
6,545,580 B2 *	4/2003	Hegde et al.	335/296

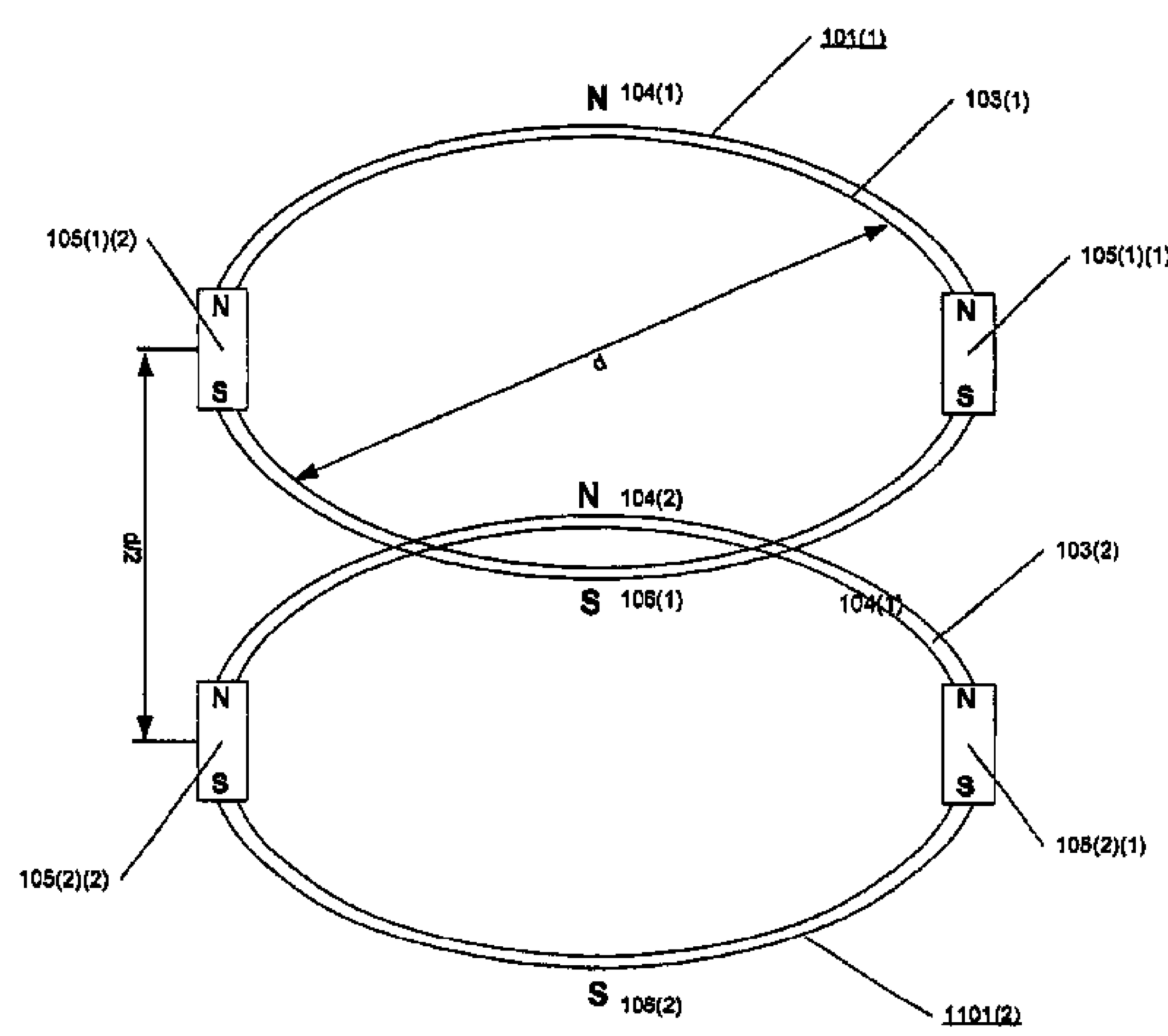
* cited by examiner

Primary Examiner—Ramon M. Barrera
(74) *Attorney, Agent, or Firm*—Gordon E. Nelson

(57) **ABSTRACT**

Techniques for producing and manipulating magnetic fields. The techniques employ the mutual repulsion of magnetic fields to create uniform magnetic fields and to manipulate the uniform magnetic fields. The uniform magnetic field is created between two planar magnets. The planar magnets have cores which describe a closed curve. Like poles of the electromagnets are connected by the cores. When the electromagnets are activated, repulsion between the magnetic fields generated by the electromagnets creates a magnetic field which extends above and below the planes of the planar magnets. If the planar magnets are positioned parallel to each other and aligned so that the magnetic fields generated by the planar magnets repel each other in the space between the planar magnets, the repulsion between the fields generates a resultant field. When the distance between the planar magnets is approximately ½ the diameter of the closed curve, the resultant field is uniform over a considerable volume of the space between the planar magnets. The uniform field may be manipulated by varying the magnitude and direction of the current provided to the electromagnets. Depending on the number and positions of the electromagnets and how power is supplied to them, the uniform field may be rotated, tilted in the horizontal and/or vertical planes, warped in the horizontal and/or vertical planes, and given gradients in the horizontal and/or vertical planes. The planar magnets may be fitted around the chambers of reactors such as those used for MERIE and the uniform field may be used to manipulate the plasma in the reactor chamber.

18 Claims, 15 Drawing Sheets



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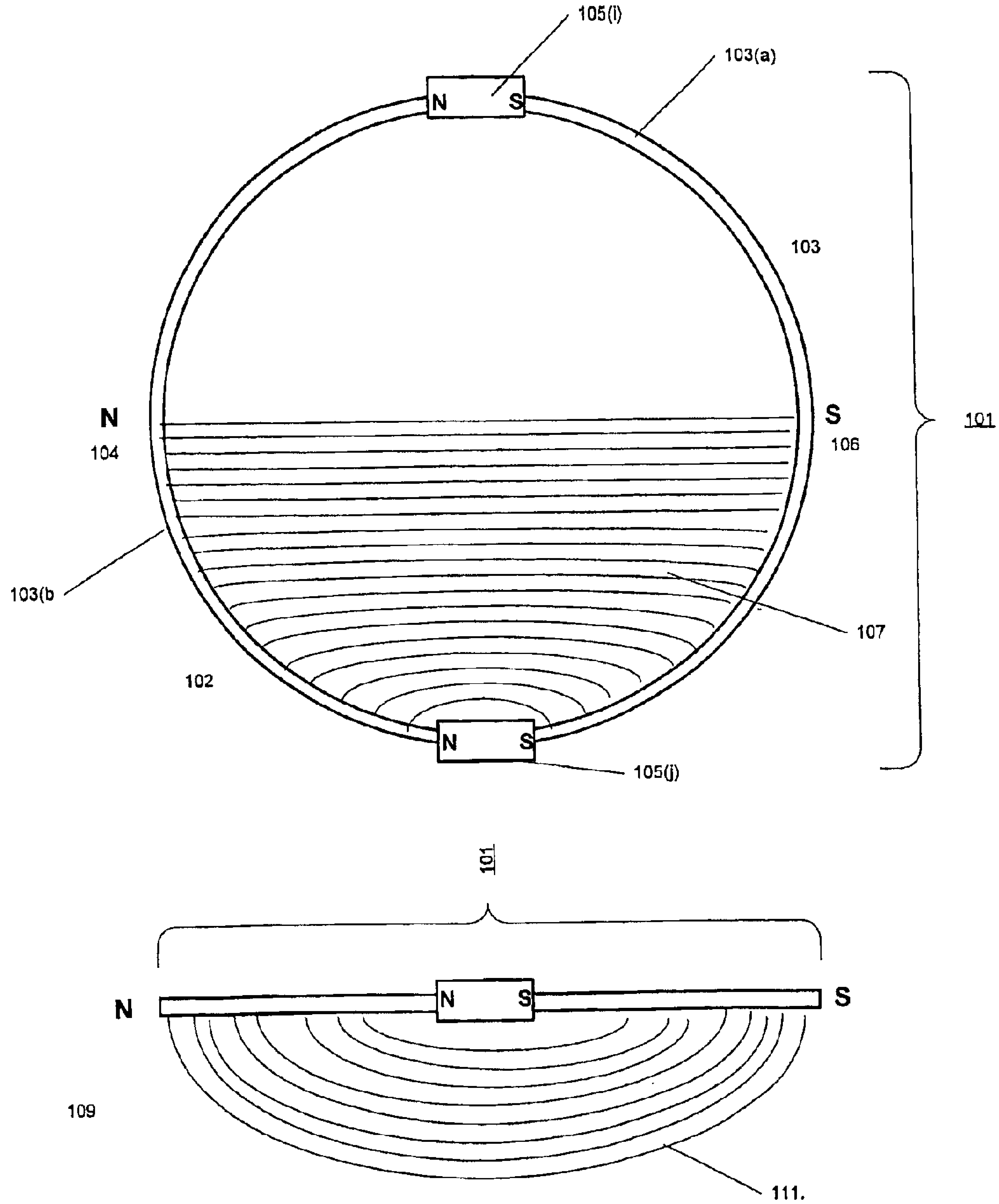
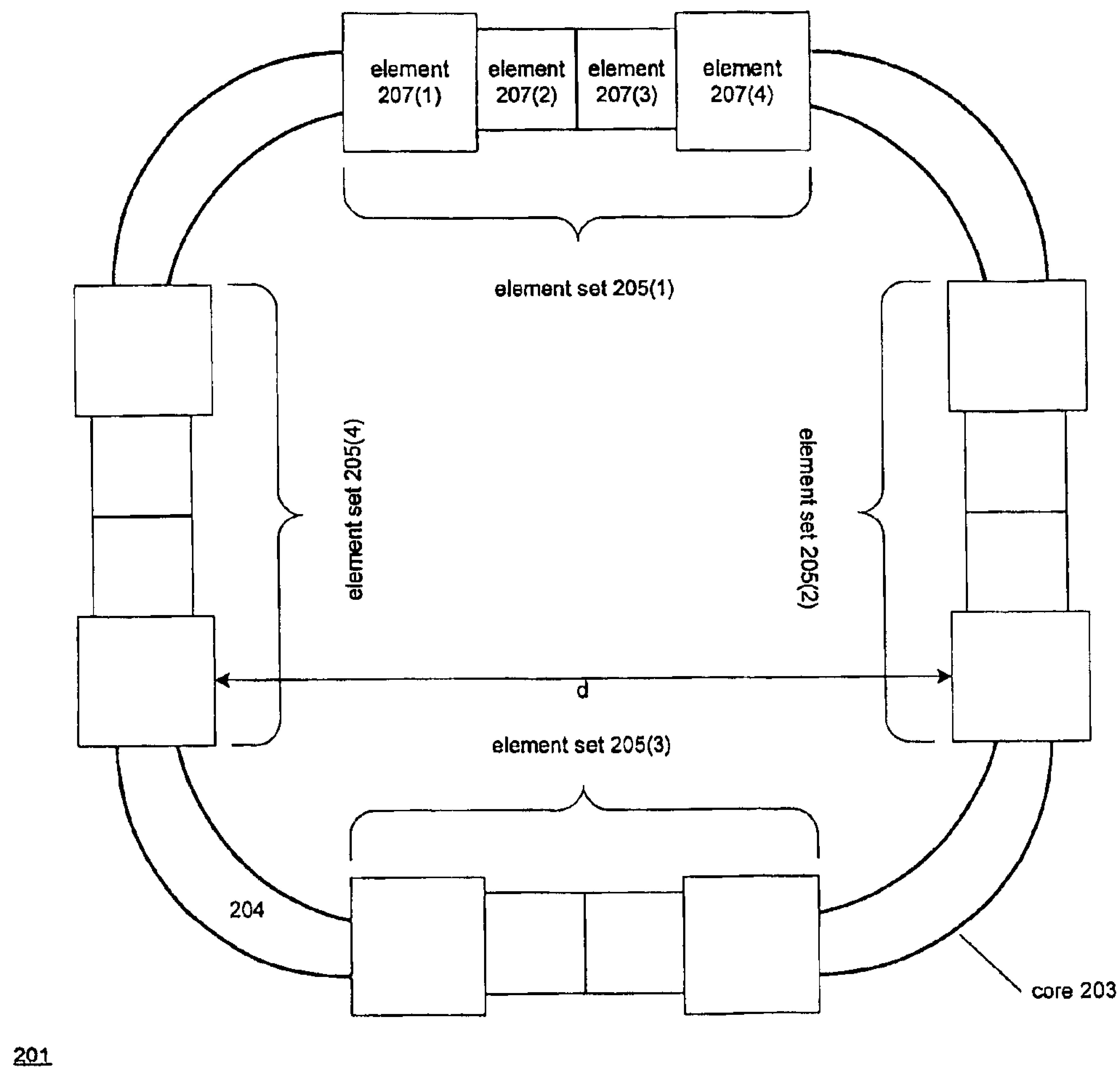

105(i)
103(a)
103
N
104
S
106
101
103(b
107
102
N
S
105(j)
101
N
S
N
S
109
111.

Fig. 1


element 207(1)
element 207(2)
element 207(3)
element 207(4)
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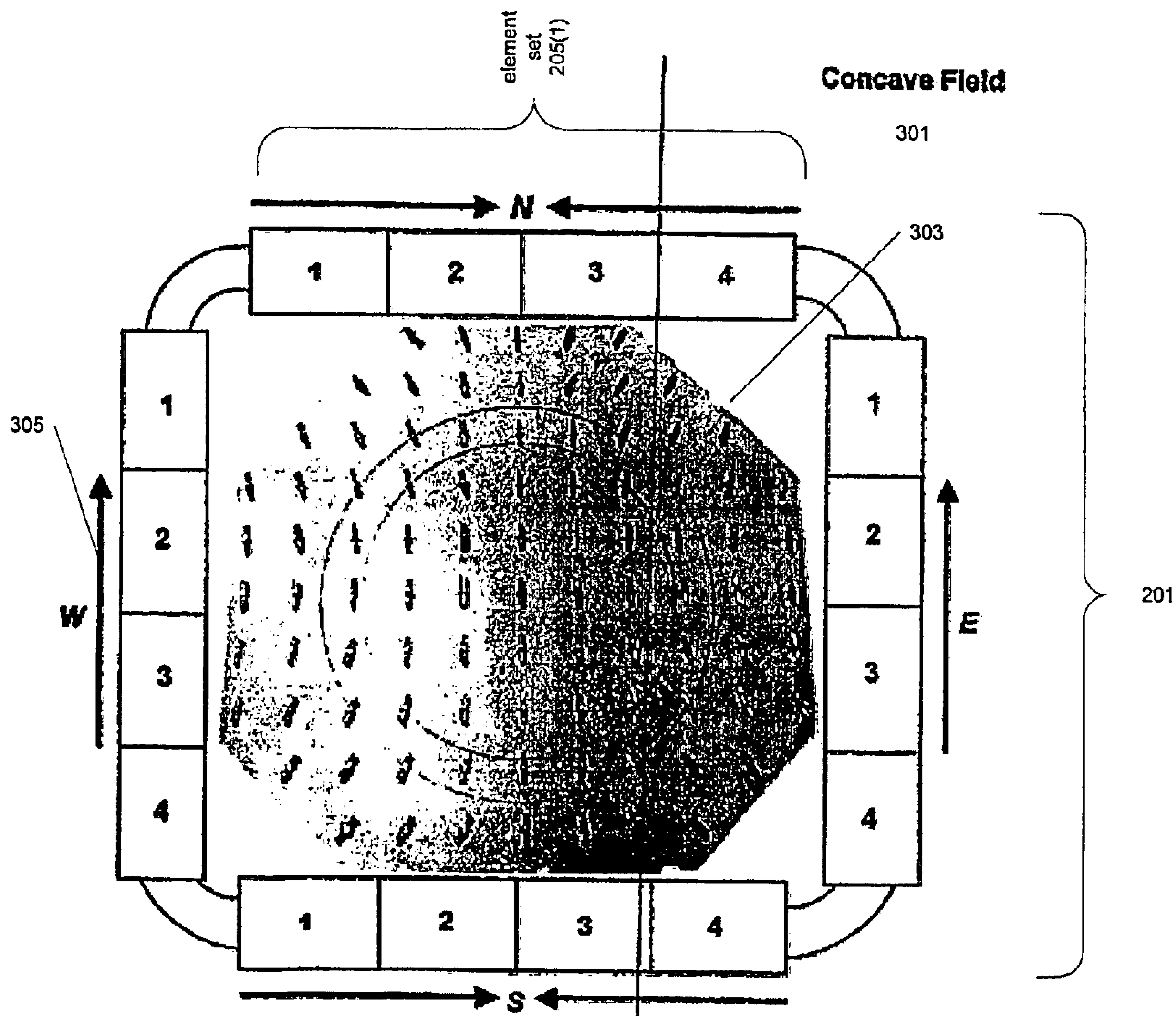
element set 205(4)
element set 205(2)
d
element set 205(3)
204
core 203
201

Fig. 2

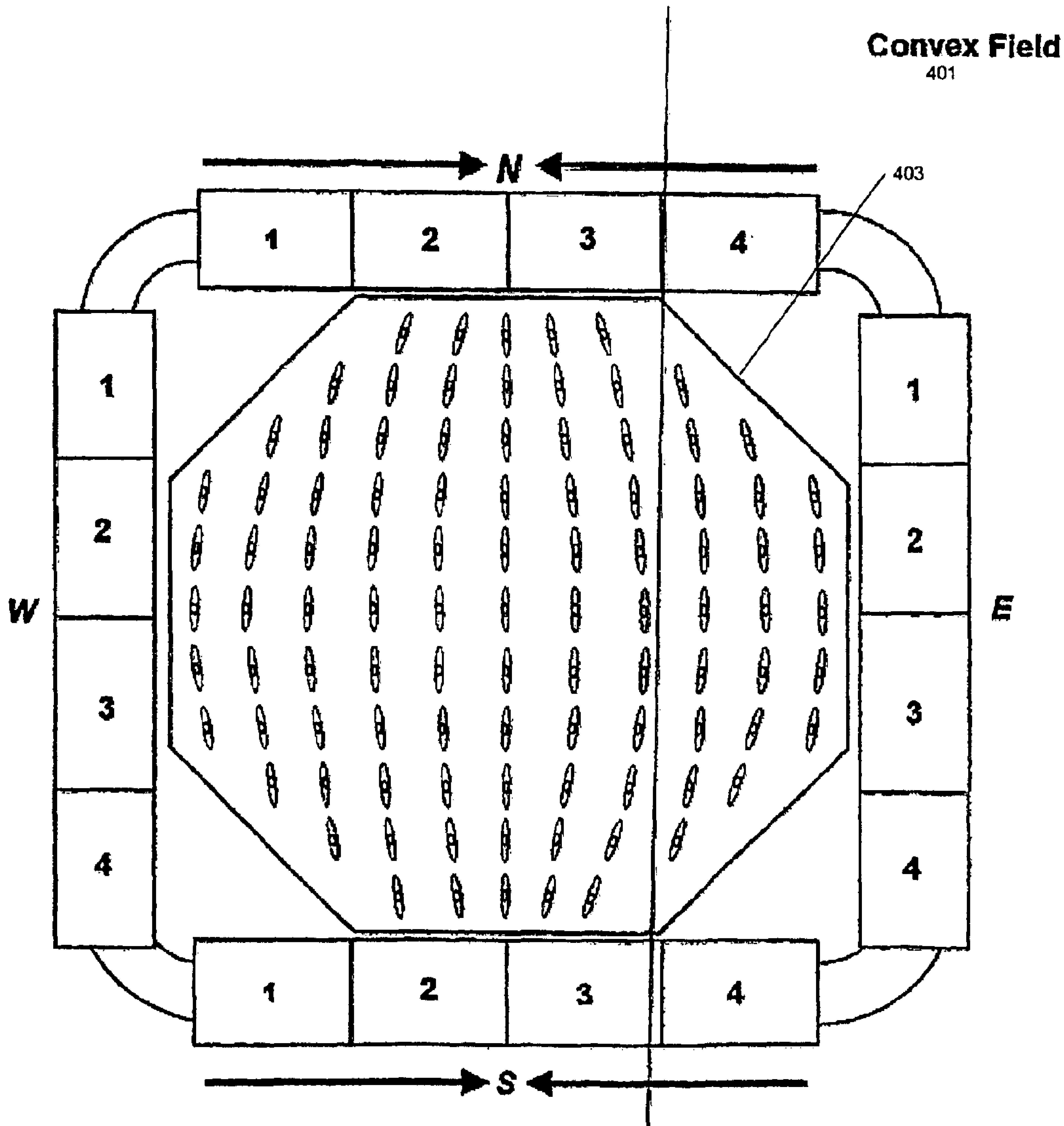


AMPERE TURNS

	COIL 1	COIL 2	COIL 3	COIL 4
NORTH	3366	2417	2417	3366
SOUTH	3366	2417	2417	3366
EAST		1722	1722	
WEST		1722	1722	

307

Fig. 3

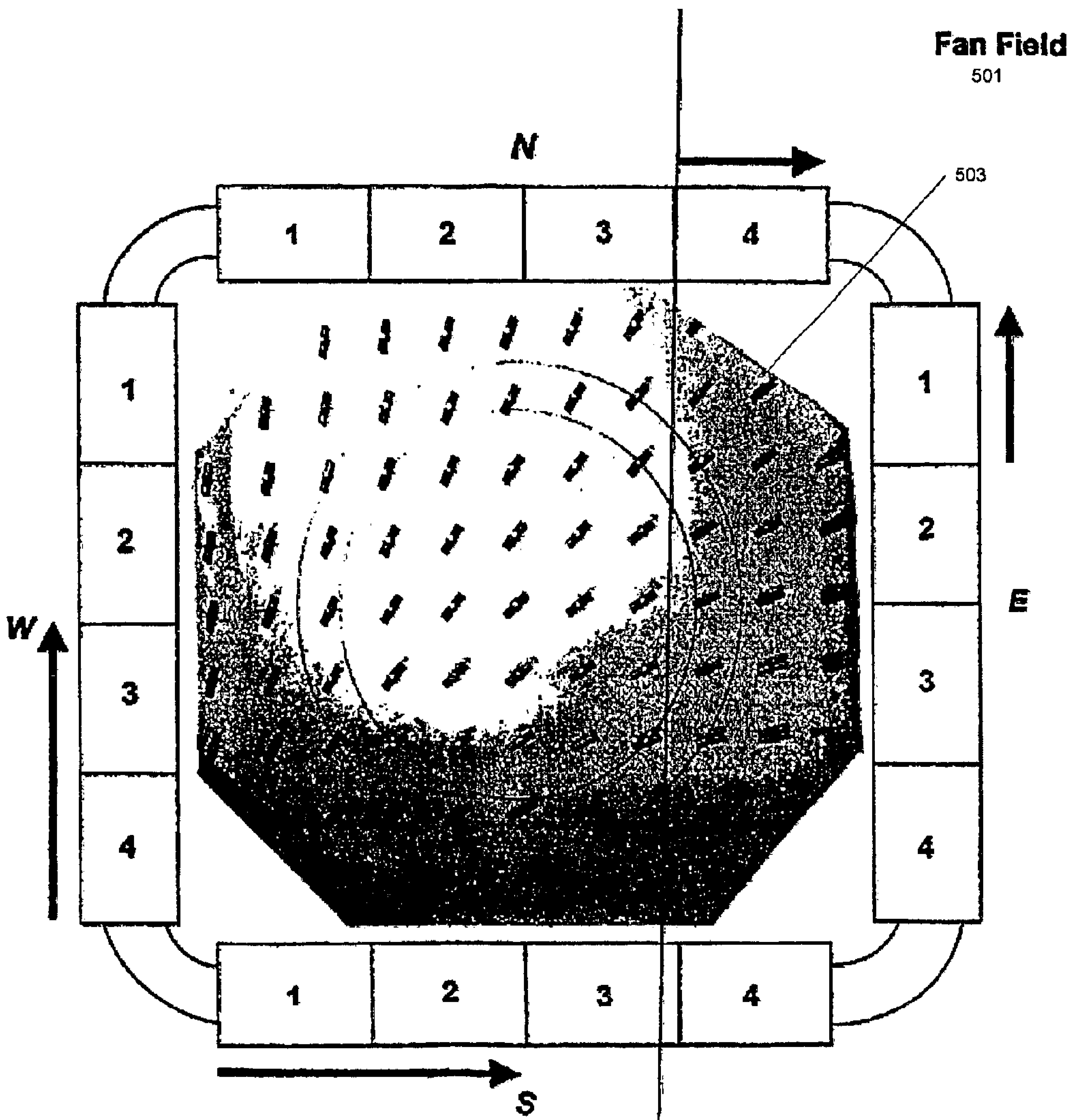


AMPERE TURNS

	COIL 1	COIL 2	COIL 3	COIL 4
NORTH	3113	2235	2235	3113
SOUTH	2904	2085	2085	2904
EAST				
WEST				

407

Fig. 4



AMPERE TURNS

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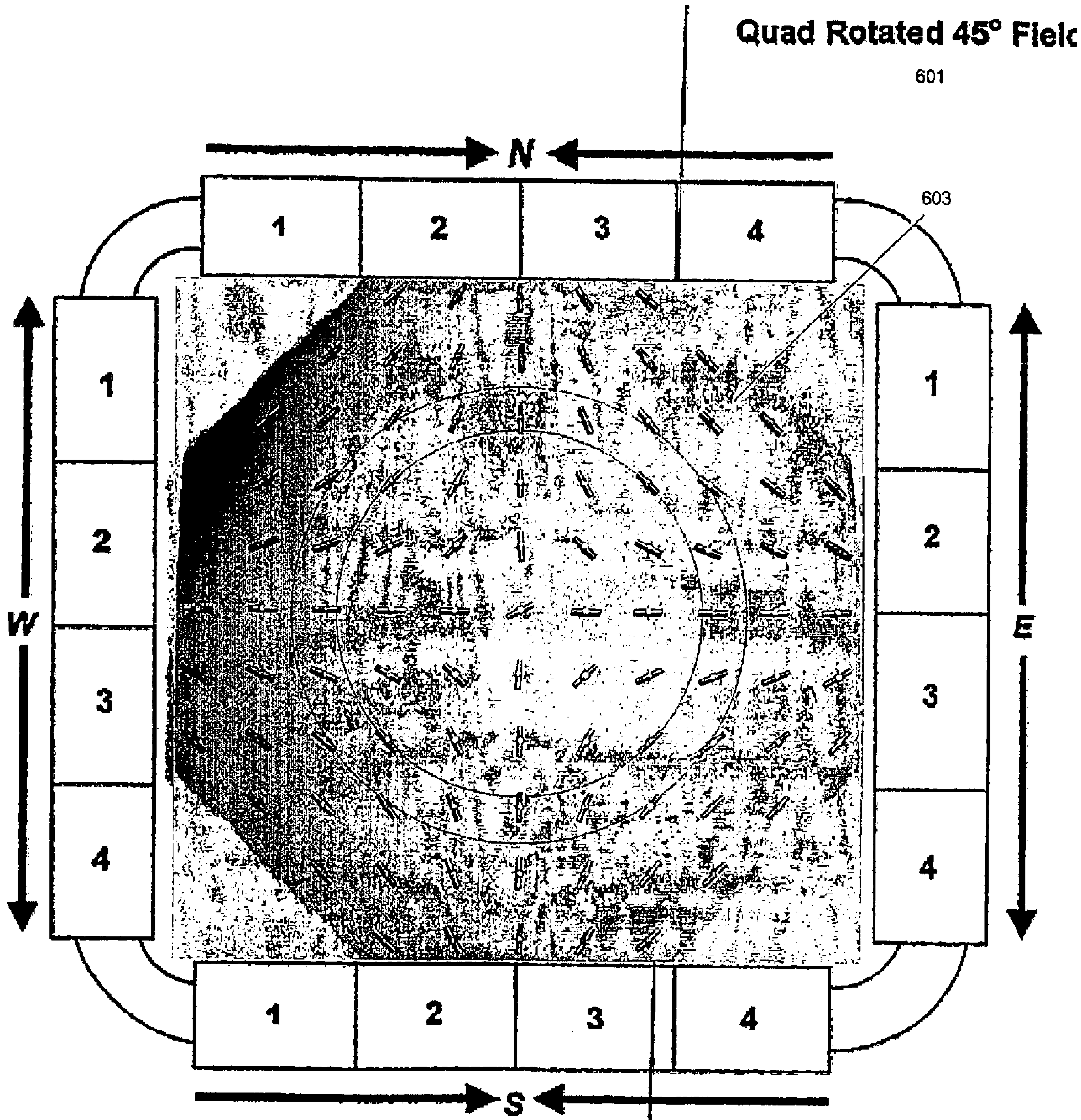
NORTH				660
SOUTH	2310	1659		
EAST	660			
WEST			1659	2310

Fig. 5



AMPERE TURNS

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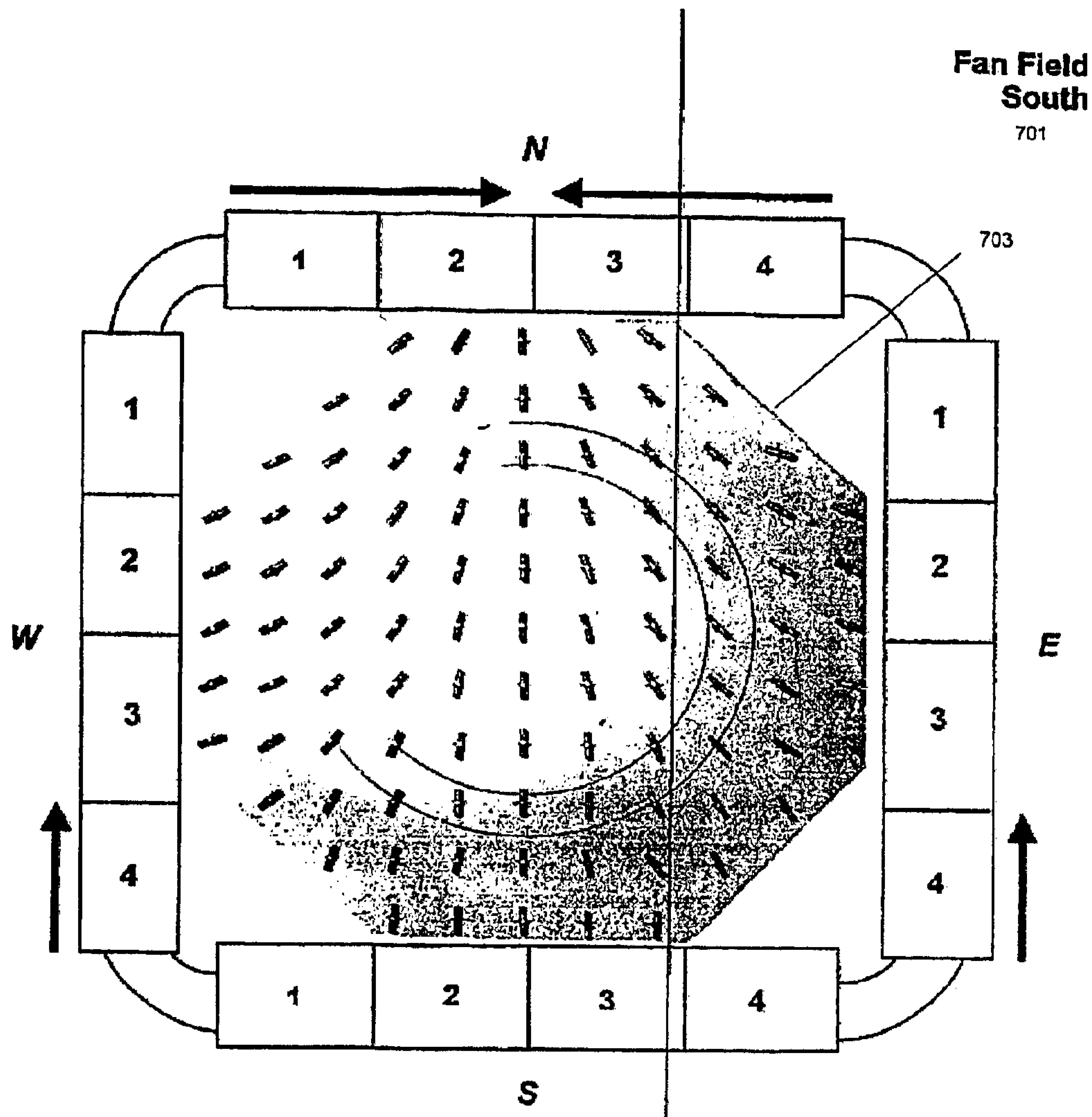
NORTH	3102	2227	2227	3102
SOUTH	2948	2117	2117	2948
EAST	3102	2227	2227	3102
WEST	2948	2117	2117	2948

607

Fig. 6



AMPERE TURNS

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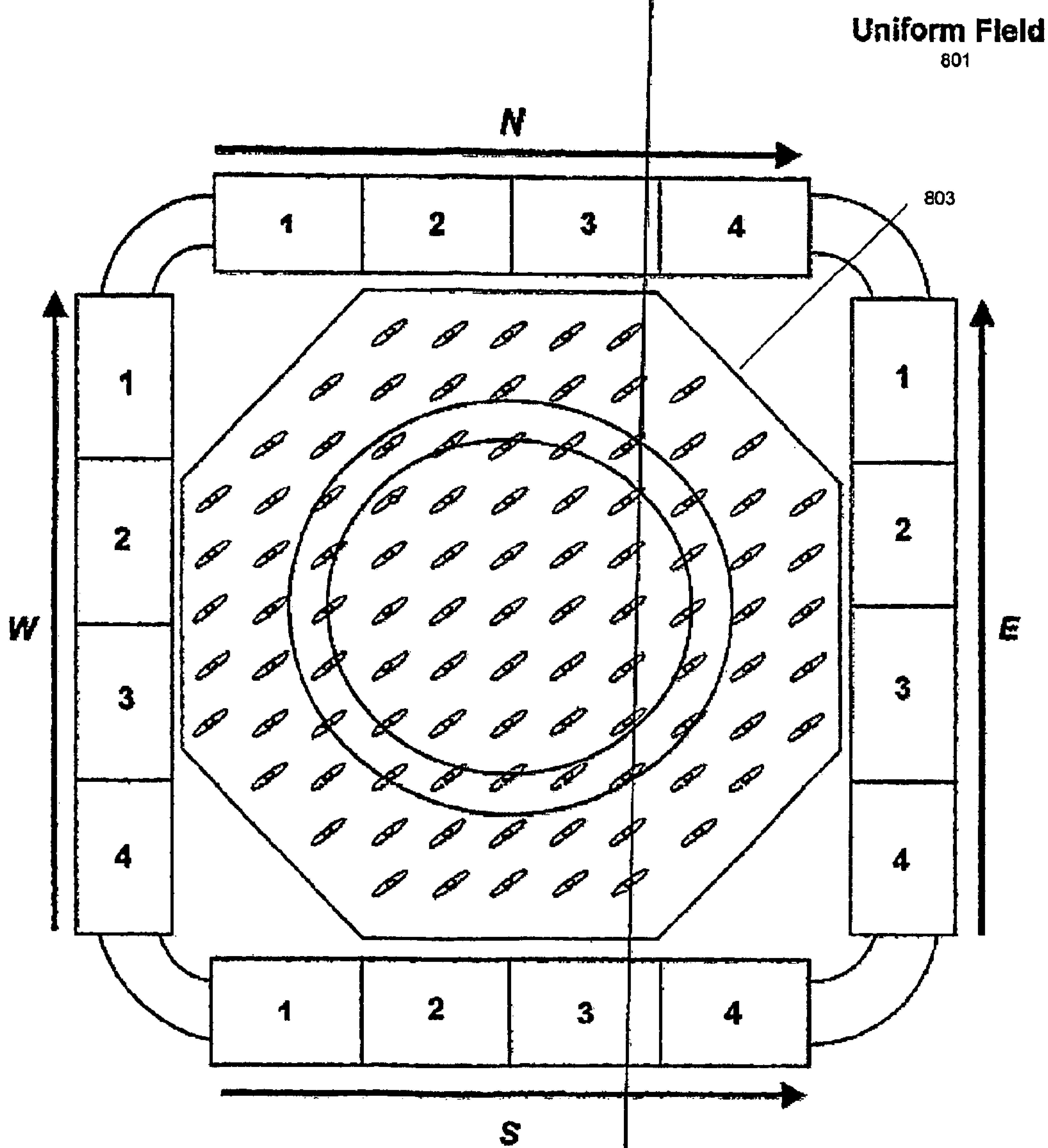
NORTH	3300	2370	2370	3300
SOUTH				
EAST				1980
WEST				1980

707

Fig. 7



AMPERE TURNS

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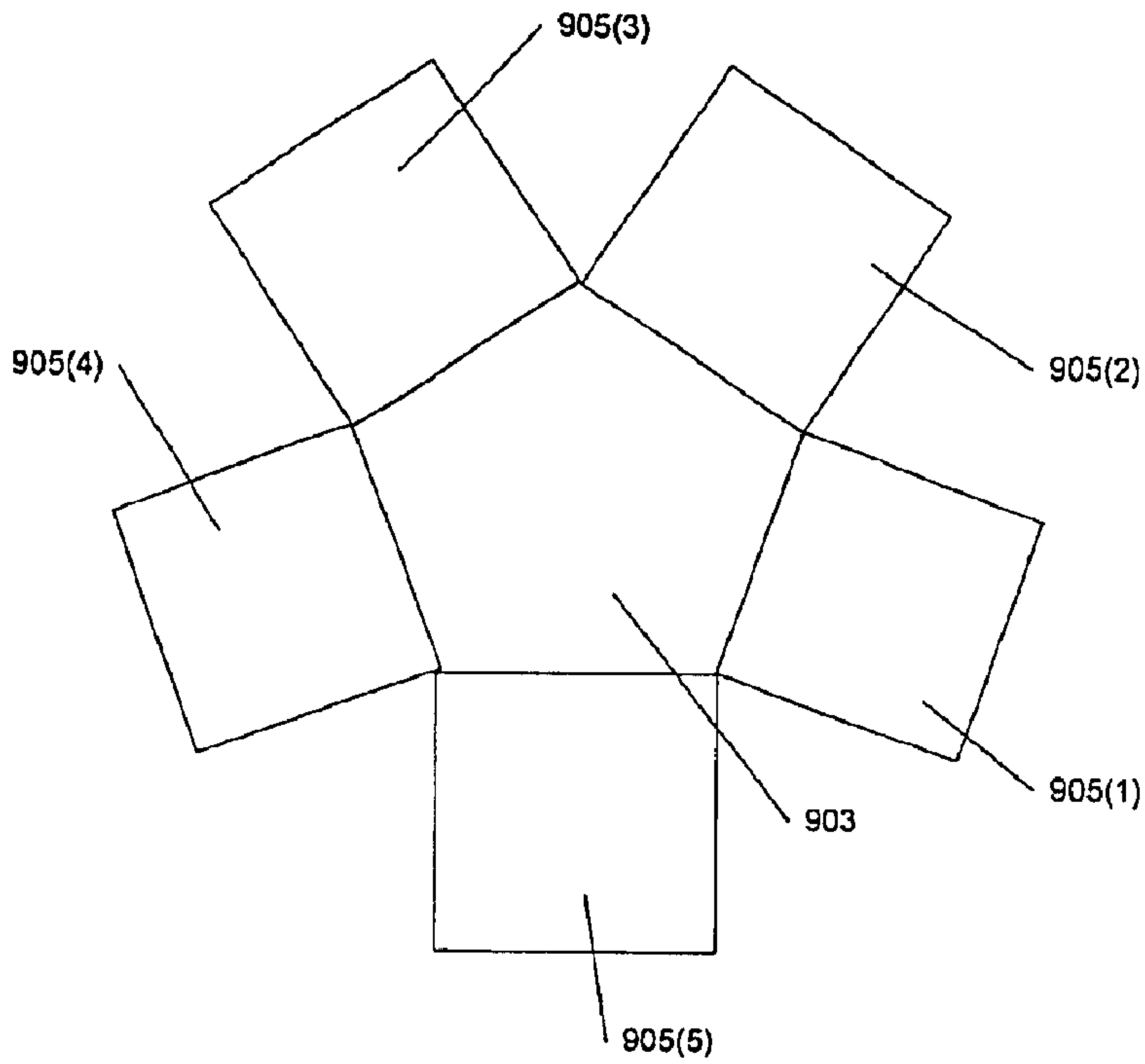
NORTH	2380	1587	1587	2380
SOUTH	2380	1587	1587	2380
EAST	2380	1587	1587	2380
WEST	2380	1587	1587	2380

807

Fig. 8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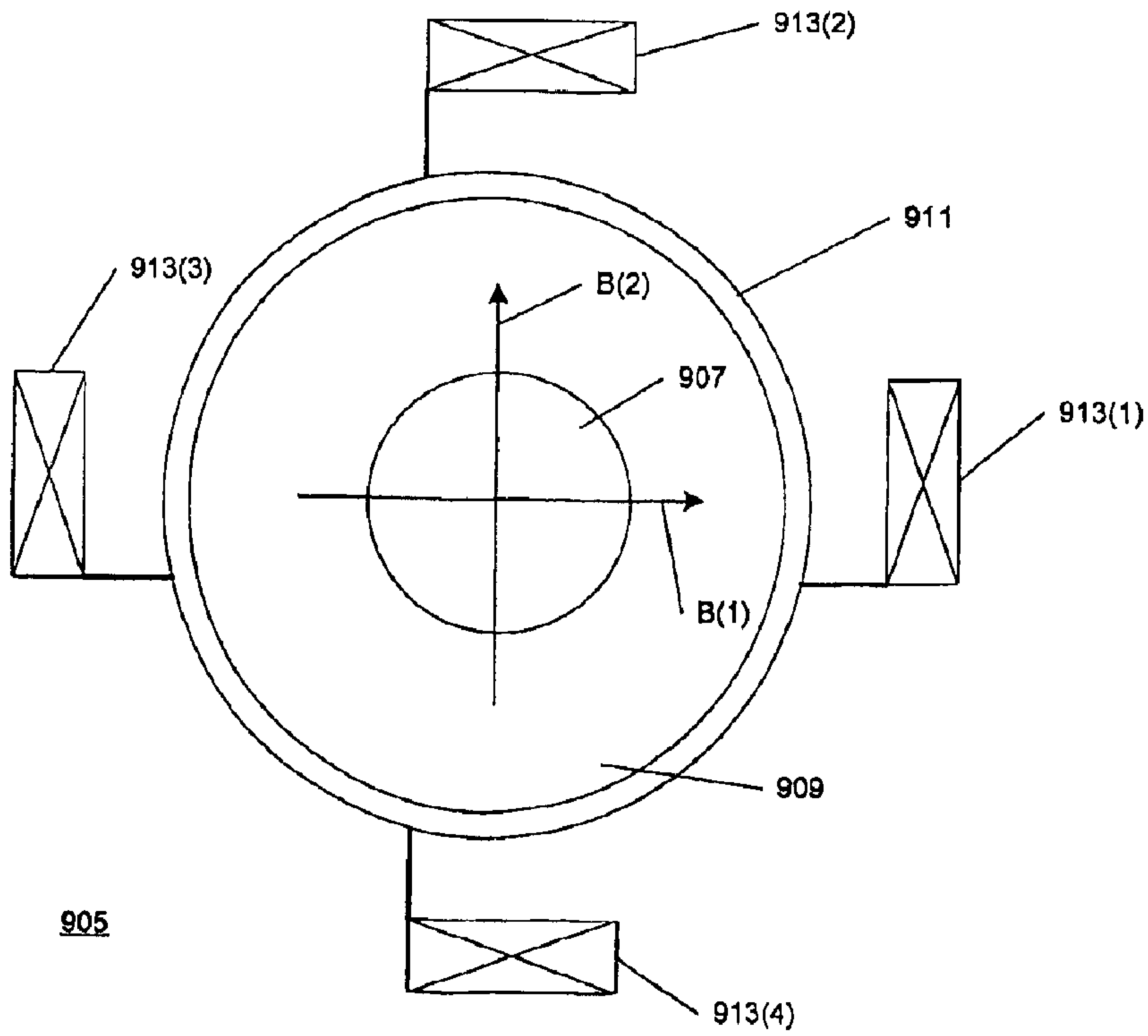
905(4)
905(1)
903
905(5)

901


913(2)
911
913(3)
B(2)
907
913(1)
B(1)
909
913(4)

905

Fig. 9

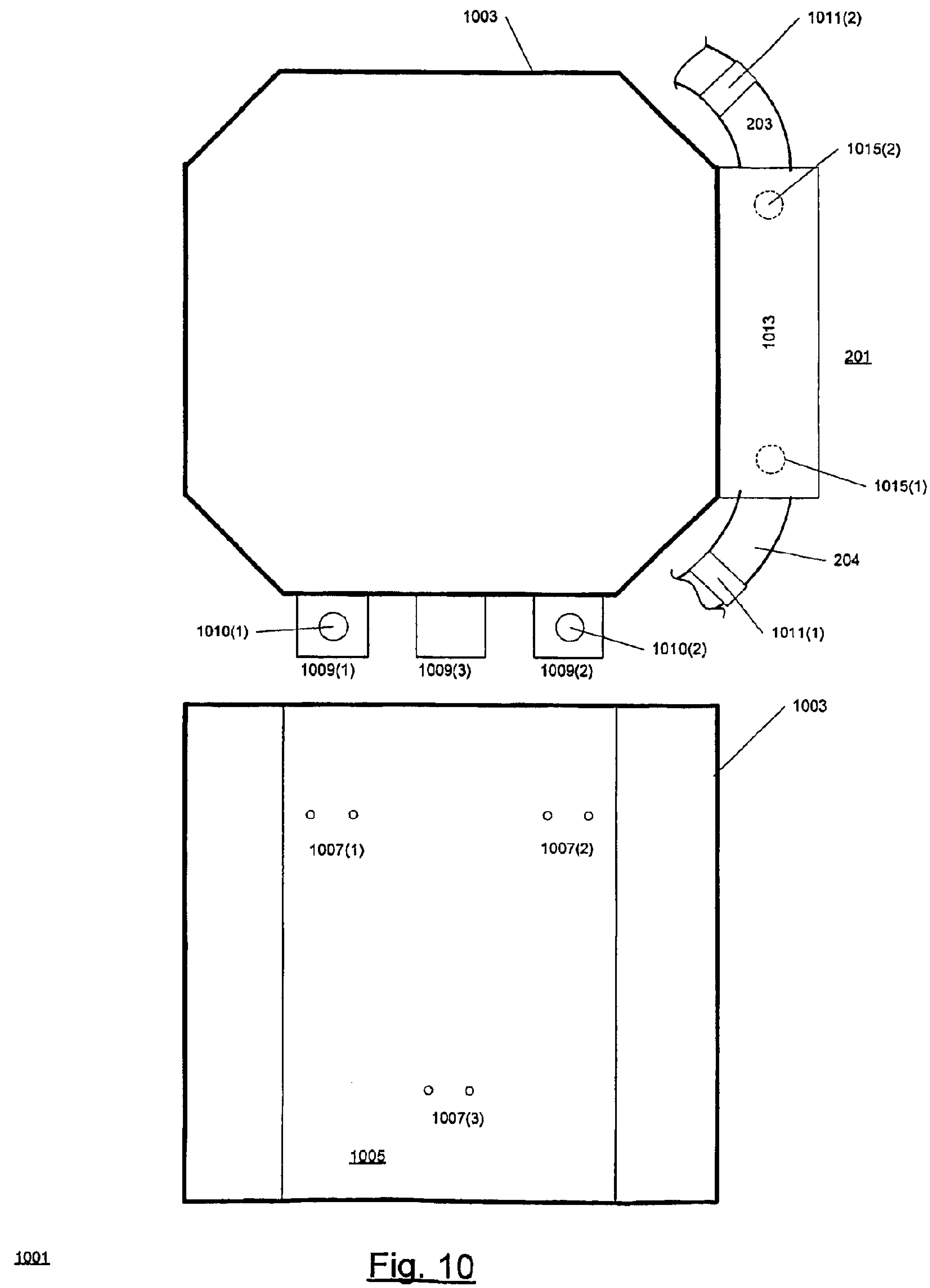
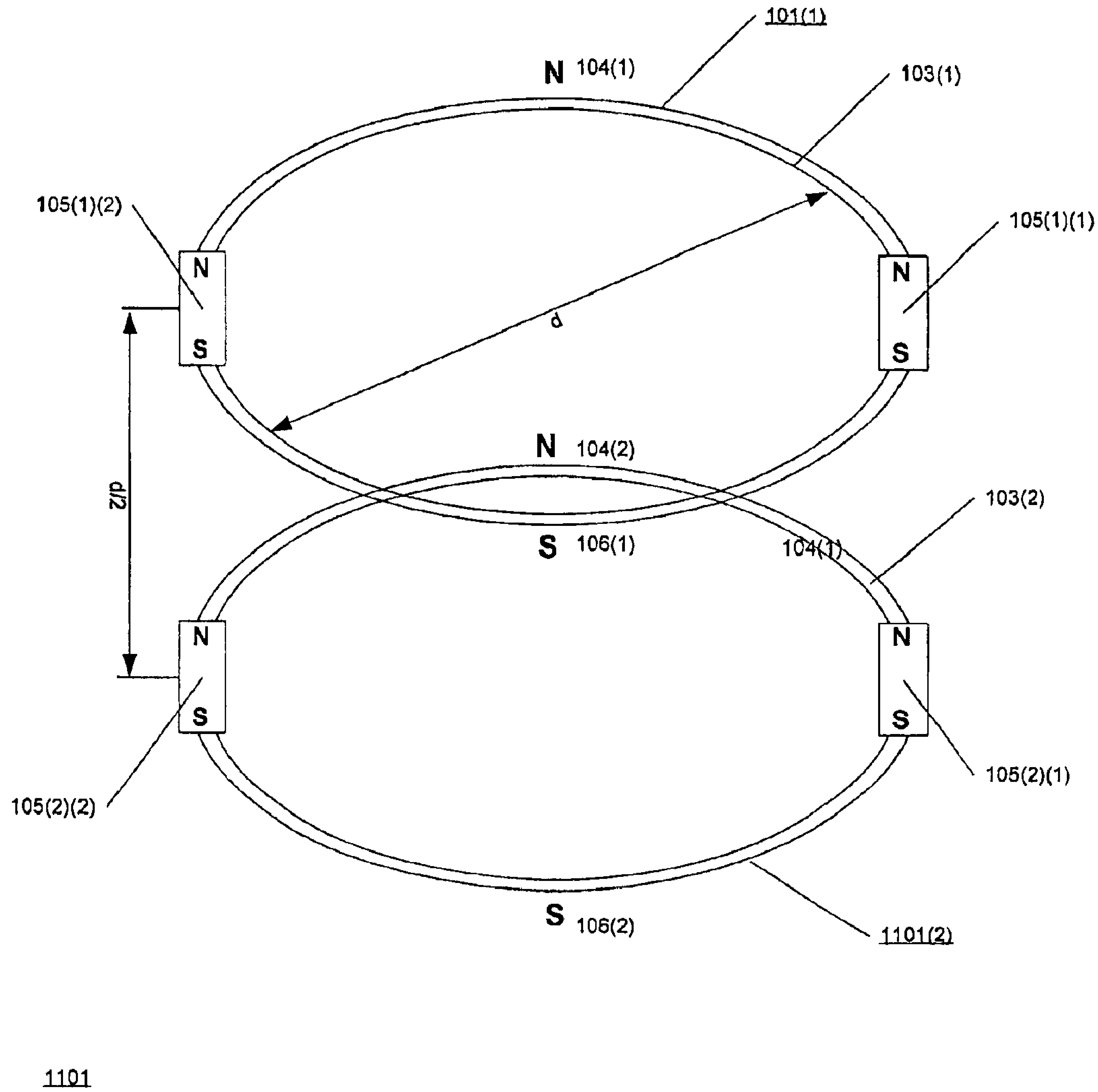
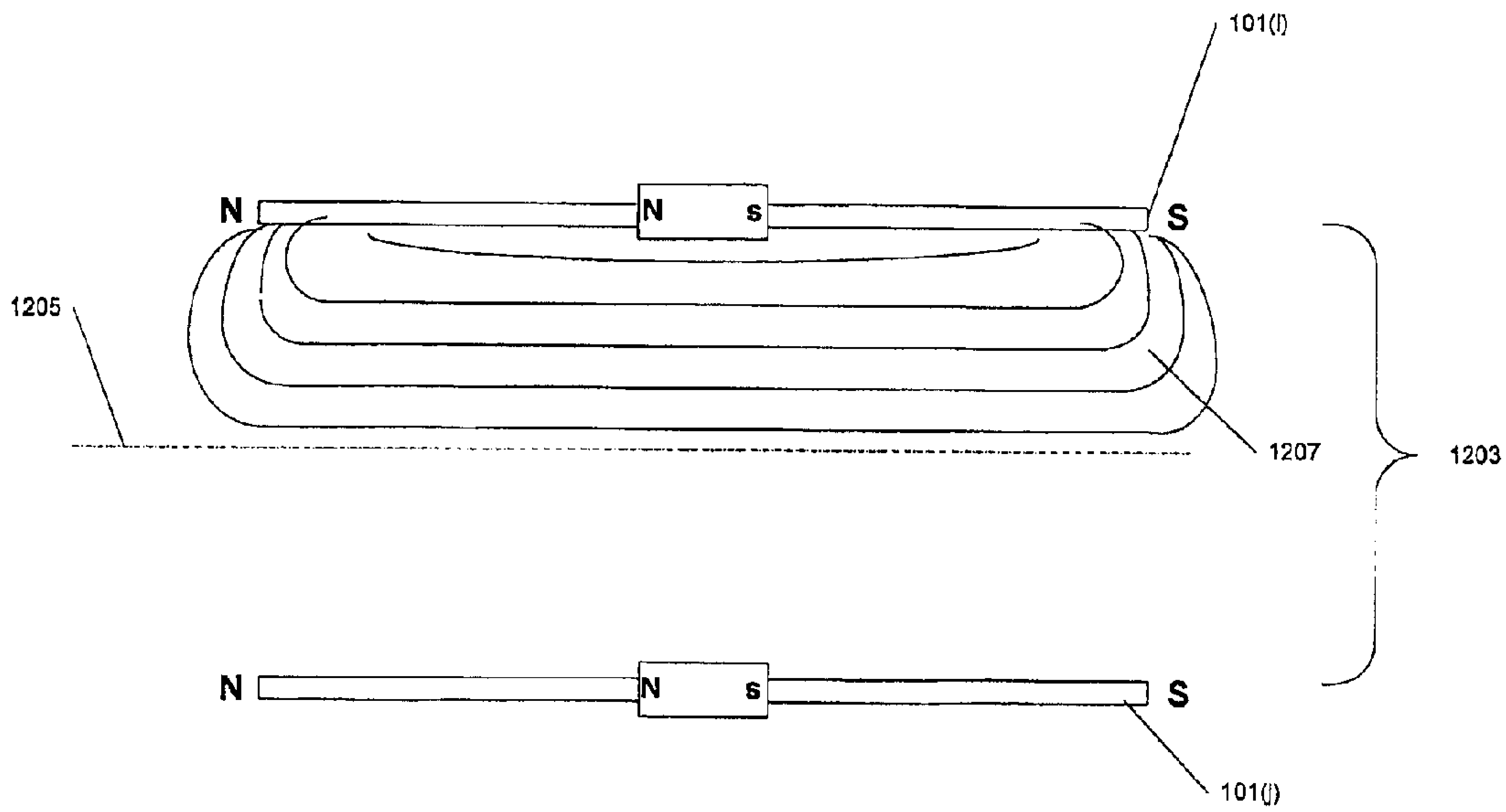

1003
1011(2)
203
1015(2)
1013
201
1015(1)
204
1011(1)
1010(1)
1010(2)
1009(1)
1009(3)
1009(2)
1003
1007(1)
1007(2)
1007(3)
1005
1001

Fig. 10



101(1)
N
104(1)
103(1)
105(1)(2)
105(1)(1)
N
S
N
S
d
d/2
N
104(2)
103(2)
S
106(1)
104(1)
N
S
N
S
105(2)(2)
105(2)(1)
S
106(2)
1101(2)
1101

Fig. 11



1101

Fig. 12

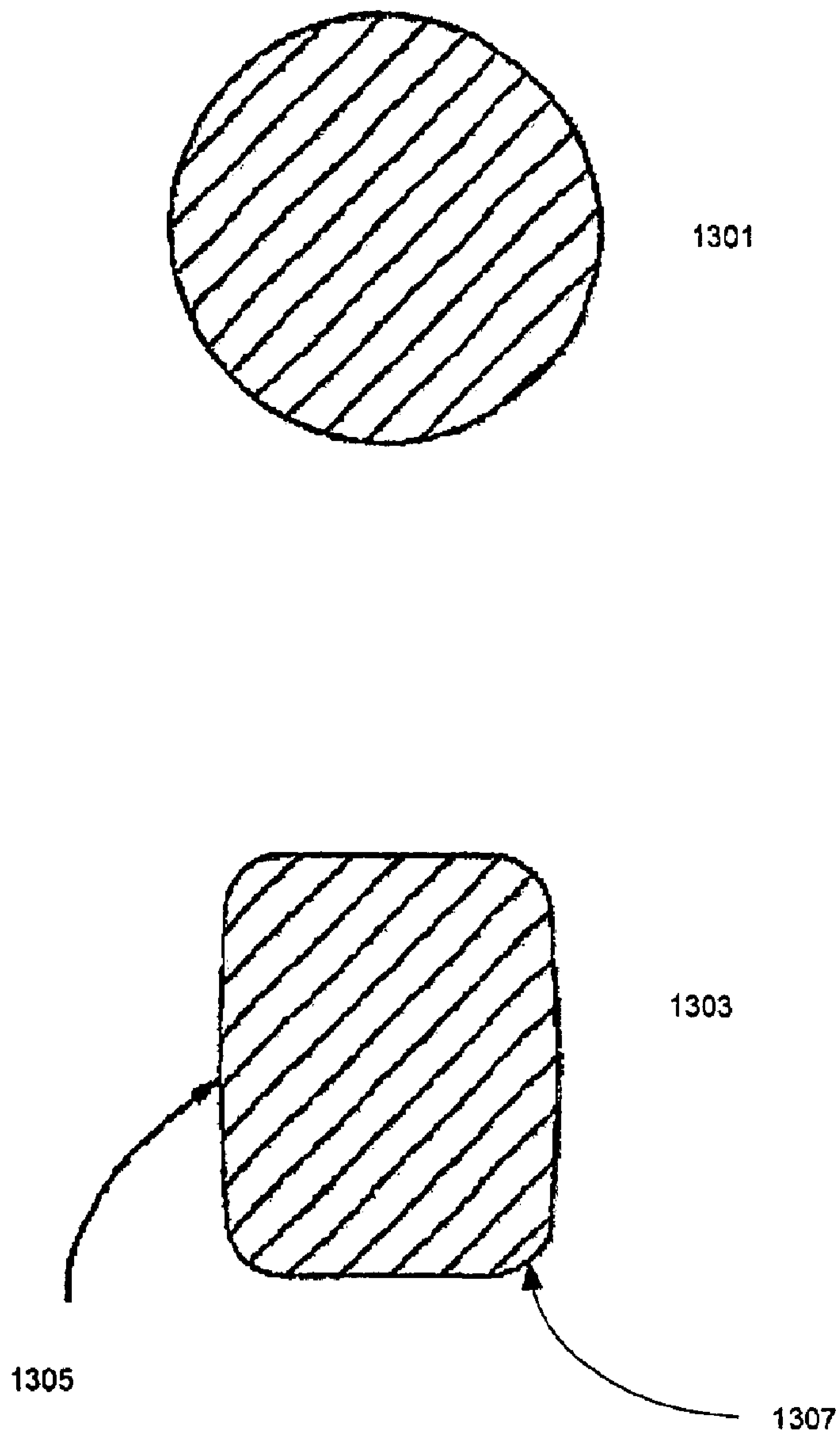


Fig. 13

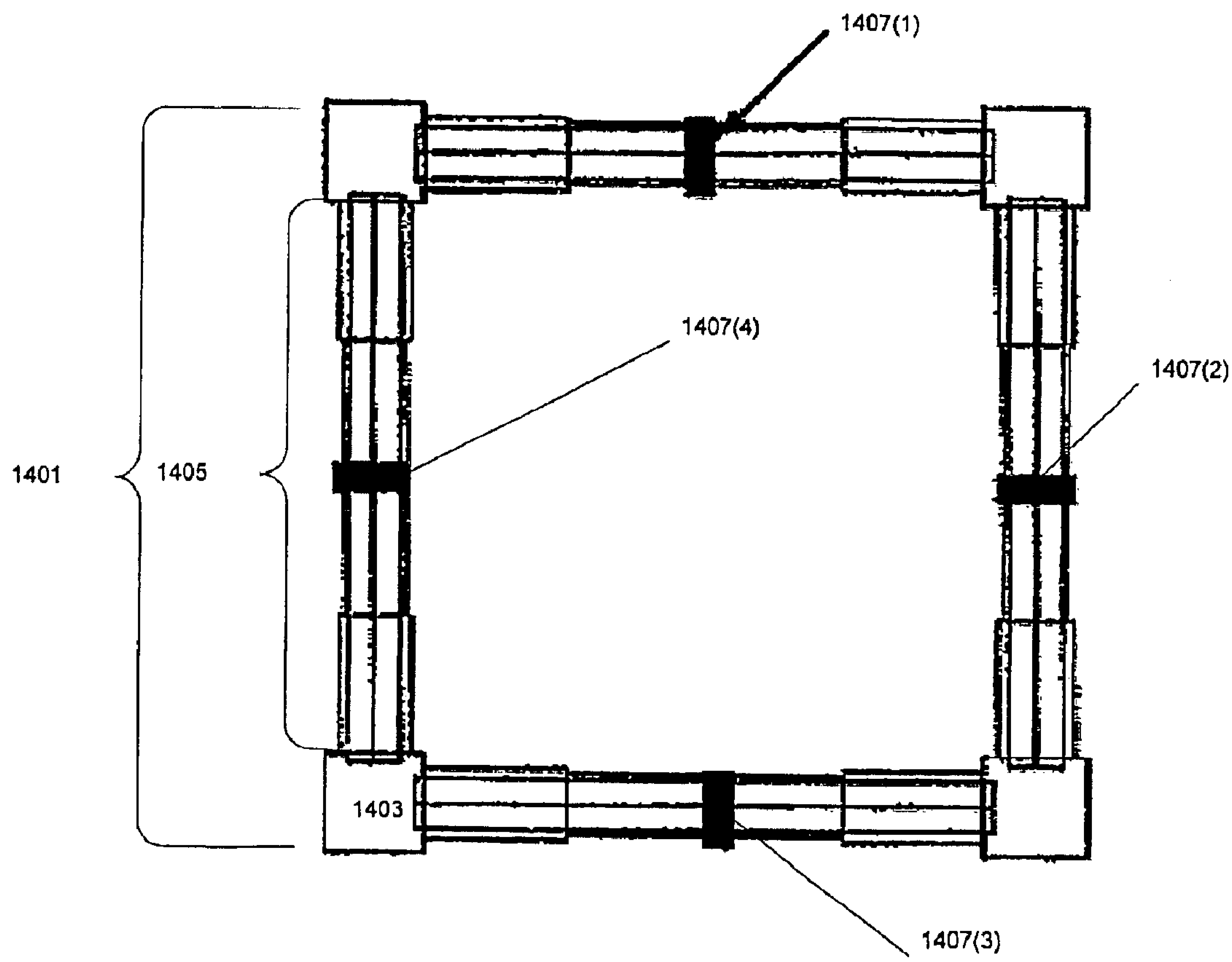
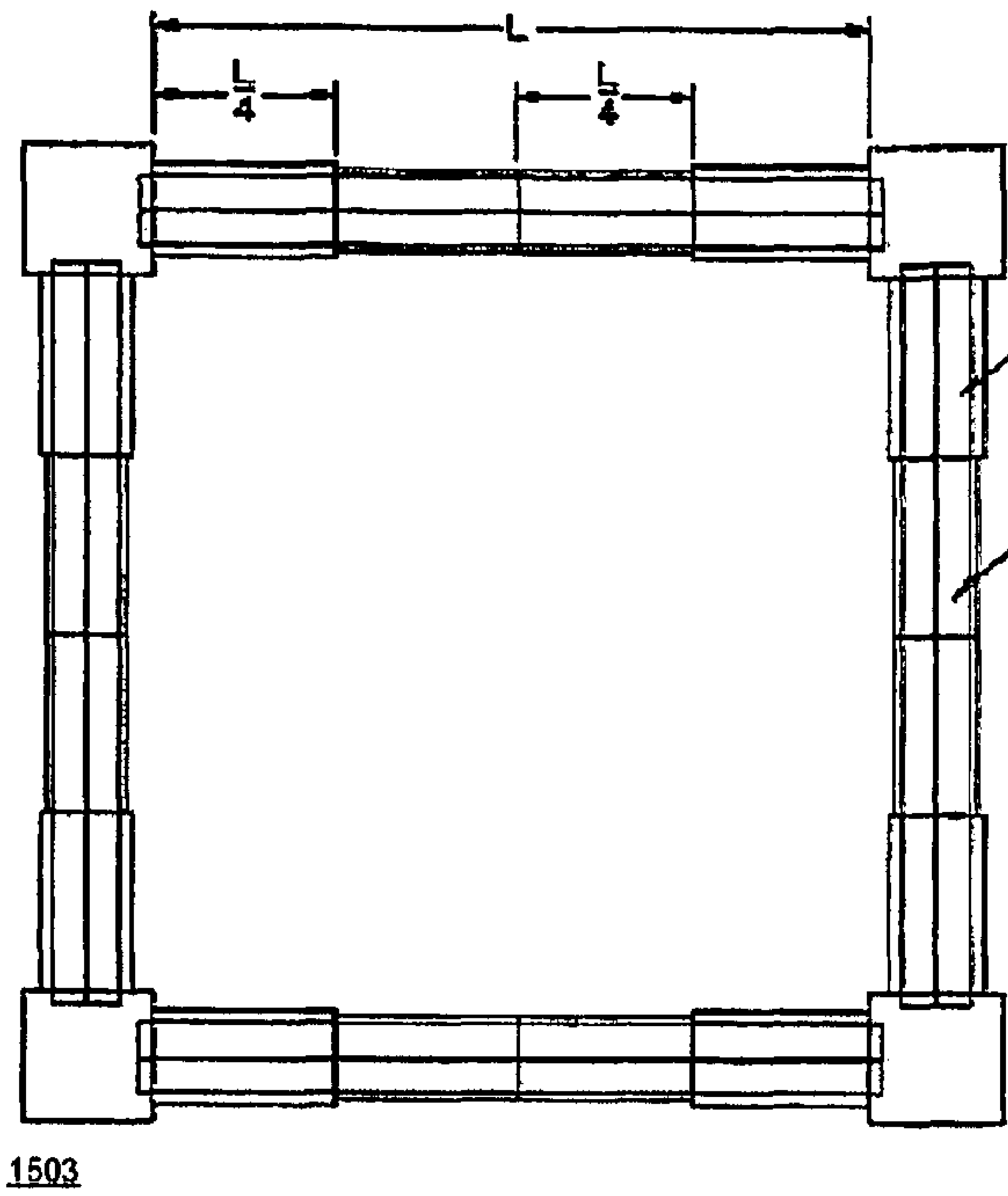
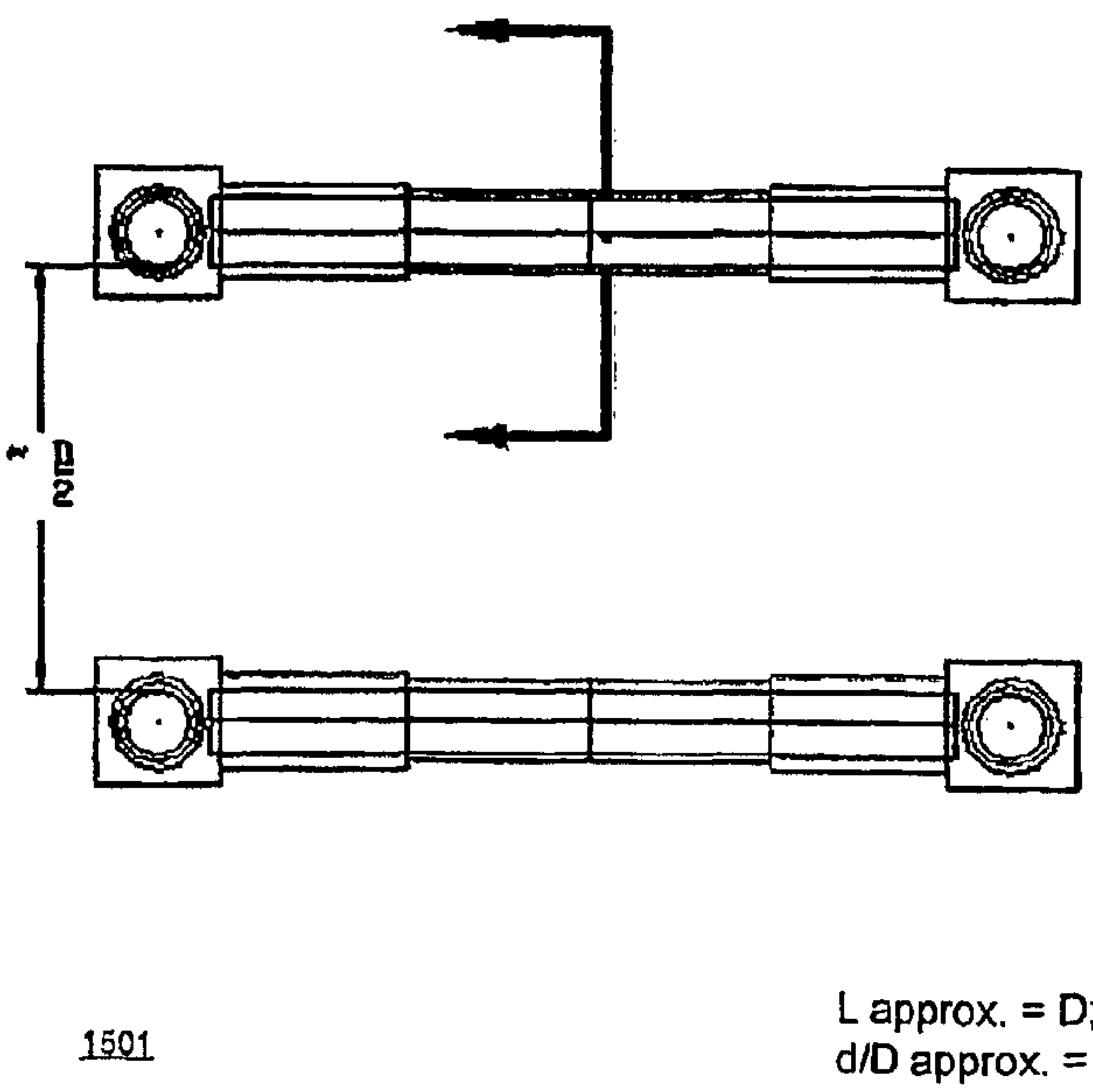
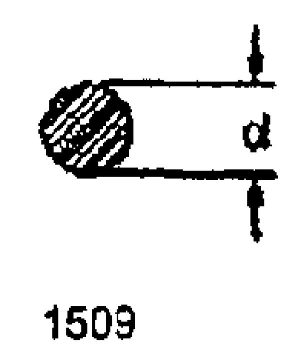


Fig. 14







L approx. = D;
d/D approx. = 0.1 for field with a maximum of 100 G

Fig. 15

APPARATUS FOR MANIPULATING MAGNETIC FIELDS

CROSS REFERENCES TO RELATED APPLICATIONS

The present patent application claims priority from U.S. provisional patent application 60/409,323, Eugene L. Oster, "Any Angle" uniform field etch plasma magnet array, filed Sep. 9, 2002 and from U.S. provisional patent application 60/486,676, Eugene L. Oster, Improved "any angle" uniform field etch plasma magnet array, filed Jul. 11, 2003, and incorporates U.S. Pat. No. 6,015,476, Schlueter, et al., Plasma reactor magnet with independently-controllable parallel axial current-carrying elements, issued Jan. 18, 2000, by reference for all purposes.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to electromagnets generally and more specifically to electromagnets used to manipulate magnetic fields in enclosed vessels.

2. Description of Related Art

Magnetic fields have long been used to manipulate particles that respond to them such as charged particles or polar particles. In one large class of such uses, electromagnets located outside a vacuum vessel or reactor vessel are used to affect the behavior of particles that respond to the magnetic fields within the vessel. Examples of such uses are focusing electromagnets in cathode ray tubes or particle accelerators and electromagnets used to manipulate plasmas in plasma reactors or to control crystal growing processes.

An exemplary use of electromagnets to manipulate plasmas is magnetic enhanced reactive ion etching, or MERIE. Part of the process of producing an integrated circuit is etching the substrate for the circuit. A common way of doing this is by reactive ion etching, in which reactive ions do the etching. The parts of the substrate which are not to be etched are covered by a mask which is resistant to the reactive ions and the masked substrate is placed in a vessel in which a plasma of reactive ions is formed from a reactive gas. The reactive ions react with the unmasked areas of the substrate and the reaction etches the substrate. In MERIE, a magnetic field is used to manipulate the plasma to keep the plasma within the area over the substrate and increase the plasma's density, which increases the rate of etching. For details on MERIE and the reactors generally used in MERIE, see the Schlueter patent cited above.

One approach to manipulating the plasma in a MERIE reactor is simply to generate a constant uniform magnetic field in the vessel that keeps the plasma where it is wanted. One way of doing this employs the principles of the Helmholtz coil. A Helmholtz coil consists of two plane circular coils of radius r whose planes are parallel to each other. The centers of the coils are on a line perpendicular to the planes and the planes are r apart. In the area between the coils, the combined fields of the coils produce a generally constant magnetic field. An example of the use of the principles of the Helmholtz coil in a chemical vapor deposition reactor may be found in U.S. Pat. No. 4,668,365, Foster et al., Apparatus and method for magnetron-enhanced plasma-assisted chemical vapor deposition, issued May 26, 1987, in which a pair of electromagnetic coils having the geometry of the Helmholtz coil are used to provide a uniform magnetic field in which material is deposited on a substrate that is perpendicular to the planes of the Helmholtz coil. An example of the use of pairs of electromagnetic coils having the geometry of the Helmholtz coil to confine the plasma in a reactor vessel to the area between the electrodes of the vessel may be found in U.S. Pat. No. 5,527,394, Heinrich, et al., Apparatus for plasma enhanced processing of substrates, issued Jun. 18, 1996.

Another way of producing a more uniform magnetic field is described in U.S. Pat. No. 5,718,795, Plavidal, et al., Radial magnetic field enhancement for plasma processing, issued Feb. 17, 1998. Here, the magnet which produces the field is located above the ceiling of the vessel. The magnet has a ferrous yoke which has a hub connected by spokes to an outer ring. The hub, spokes, and ring form a shallow cone. The spokes have windings which are connected to an AC, DC, or RF power supply. The angle of the spokes is chosen to produce a relatively uniform radially symmetrical magnetic field at the level of the substrate.

A way of dealing with non-uniform plasmas is to use the electromagnets not only to keep the plasma where it is wanted, but to move the plasma. The most common arrangement for doing this is described in the Background Art portion of the Schlueter patent. Four electromagnetic coils are mounted 90° from each other on the sides of the vessel. The coils have vertical legs and horizontal legs, with the horizontal legs sometimes being bent to conform to the curve of the sides of the vessel. While the magnetic field produced by an opposed pair of the electromagnetic coils is not particularly uniform, the field can be rotated by varying the amount and direction of current in pairs of opposite coils. Rotation may be achieved by switching the current in the coils or more smoothly by applying AC currents to the coils in the amounts, phases and frequencies required to rotate the magnetic field. Slowly rotating the plasma in this fashion reduces the exposure of the circuitry in the substrate to irregularities in the plasma which can damage the circuitry.

Though the electromagnetic coils on the sides of the vessel permit rotation of the magnetic field, the lack of uniformity of the magnetic field both causes irregularities in the plasma and these in turn may lead to damage in the substrate. One way of producing a more uniform rotating magnetic field is described in the Schlueter patent; there, the magnetic field is generated by a number of coils wound on a ferrous cylinder that surrounds the outside of the vessel that contains the substrate at the position of the substrate. On the inside of the ferrous cylinder, the windings are parallel to the vertical axis of the vessel. The main function of the ferrous cylinder is to shield the windings on the inside of the ferrous cylinder from the windings on the outside of the cylinder. The windings on the inside of the ferrous cylinder generate a magnetic field in the area of the substrate. The field can be varied by varying the amounts of current provided to the different coils and the field can be rotated by varying the amounts and directions of the current in the coils according to a periodic pattern.

None of the foregoing techniques for producing magnetic fields inside a reactor vessel provides a perfect solution for MERIE. Ideally, it should be possible not only to produce a uniform magnetic field but also to produce a magnetic field with controlled gradations across the plane of the substrate and/or along the vertical axis of the vessel, and it should be possible to rotate or otherwise move whatever field is produced. It is further desirable to be able to retrofit current reactors employing coils on the sides of the vessels to produce rotating magnetic fields with electromagnets that are capable of producing highly-uniform rotating magnetic fields without affecting the retrofitted reactor's power supplies or arrangements for inserting and removing substrates or providing gaseous inputs.

It is thus an object of the invention disclosed herein to provide electromagnets which are capable of producing uniform magnetic fields, magnetic fields with controlled gradations in either the horizontal or vertical directions, and magnetic fields which can be rotated and moved and which can further be retrofitted to existing reactor vessels that employ coils on the sides of the vessels.

SUMMARY OF THE INVENTION

The object of the invention is achieved by apparatus for producing a magnetic field that includes two sets of magnetic elements. Each set defines a separate surface and produces a separate magnetic field by repulsion between the magnetic elements in the set. The set's magnetic field extends above and/or below the surface. The sets of magnetic elements are positioned relative to each other such that the surfaces are approximately parallel and the magnetic field produced by the apparatus is formed between the surfaces by repulsive interaction of the sets' magnetic fields. One or more of the magnetic elements may be an electromagnetic element and the magnetic field produced by the apparatus may be manipulated by changing the direction and/or magnitude of the current in selected ones of the electromagnetic elements. If each set includes two pairs of electromagnetic elements, the magnetic field may be manipulated to impart a rotary motion to the magnetic field.

In a particularly useful version of the apparatus, the magnetic elements comprise a pair of magnetic elements, the like poles of the elements in the pair being connected by a core and the first and second sets of magnetic elements being positioned relative to each other such that a portion of the magnetic field produced by the apparatus is uniform. More particularly, the magnetic elements in the pair are separated in the surface by a distance D and the surfaces are separated by a distance D/2. If each set contains two pairs of electromagnetic elements whose like poles are connected by the core, a rotary motion may be imparted to the uniform field by changing the direction and/or magnitude of the current in the pairs of electromagnetic elements. The uniform field may also be manipulated in other ways by changing the direction and/or magnitude of the current in the electromagnetic elements. An important use of the uniform field is manipulating particles in a vessel.

In another aspect, the invention is an electromagnet that may be used as one of the electromagnets in the apparatus for producing a magnetic field. In still another aspect, the invention is a kit for retrofitting a reactor vessel that employs magnetic enhancement with the apparatus for producing a magnetic field.

Other objects and advantages will be apparent to those skilled in the arts to which the invention pertains upon perusal of the following Detailed Description and drawing, wherein:

BRIEF DESCRIPTION OF THE DRAWING

FIG. **1** shows the magnetic field generated by an electromagnet consisting of two coils on opposite sides of a circular core which are powered such that the poles of coils oppose each other;

FIG. **2** shows a preferred embodiment **201** of an electromagnet **101**;

FIGS. **3–8** show magnetic fields produced by a Helmholtz core arrangement which employs a pair of magnets **201**;

FIG. **9** shows a system of MERIE vessels which may be retrofitted with electromagnets **201**;

FIG. **10** shows details of the arrangements for retrofitting a vessel with an electromagnet **201**;

FIG. **11** shows an overview of a Helmholtz core arrangement that uses the magnets **105**;

FIG. **12** shows magnetic fields produced by the Helmholtz core arrangement of FIG. **11**;

FIG. **13** shows different cross sections for a core of an electromagnet **201**;

FIG. **14** shows how non-magnetic shims may be used for fine adjustments in an electromagnet **201**; and

FIG. **15** shows details of a preferred embodiment of an electromagnet **201**.

Reference numbers in the drawing have three or more digits: the two right-hand digits are reference numbers in the drawing indicated by the remaining digits. Thus, an item with the reference number **203** first appears as item **203** in FIG. **2**.

DETAILED DESCRIPTION

The following Detailed Description will first present an overview of the invention, will then disclose a preferred embodiment of an electromagnet that may be used in the invention, and will finally disclose how existing reactor vessels may be retrofitted with the invention.

Overview of the Invention

The following overview will first describe a type of magnet used in the invention in which the magnetic field is produced using opposed magnetic elements, will then describe how magnetic fields may be made by arranging such magnets above each other, and will finally describe a particularly useful arrangement of such magnets which is termed herein a Helmholtz core arrangement.

A Magnet in Which the Magnetic Field is Produced by Opposing Magnetic Elements: FIG. 1

FIG. **1** shows a magnet **101** in which two active magnetic elements **105**(*i*) and (*j*) of equal strength are connected by a circular core **103** of a magnetically permeable material. The magnetic elements may be either electromagnets or permanent magnets. A top view of the magnet is shown at **102** and a side view at **109**. The magnetic elements **105**(*i*) and (*j*) are arranged as shown in FIG. **1**: namely, one side of core **103** connects the north poles of the elements **105** and the other side connects the south poles of the elements.

The part of the magnetic field that results from this arrangement which is inside core **103** is shown as viewed from the top at **107** and as viewed from the side at **111**. The magnetic field is represented by field lines. Top view **107** shows the field lines as viewed from above and side view **111** shows the field lines as viewed from the side. Because the poles of magnets **105**(*i*) and (*j*) connected by the cores are opposed, the magnetic field is forced out of the cores and north pole **104** for the entire magnet **101** is equidistant between magnetic elements **105**(*i*) and (*j*) on core portion **103**(*b*), while south pole **106** for the entire magnet **101** is equidistant between magnetic elements **105**(*i*) and (*j*) on core portion **103**(*b*). Seen from the top, the field lines within the circle defined by magnet **101**'s core run as shown at **107**. Only ½ of field **107** is shown here; the other half is symmetrical to what is shown here. As seen from the top, field lines appear as curves that approach straight lines as the parts of the opposite sides of the core connected by the lines of force approach north pole **104** and south pole **106**. Because magnetic fields running in the same direction repel each other, the magnetic field lines as seen from above are distributed uniformly across the circle defined by core **103**. In the area in the neighborhood of north pole **104** and south pole **106**, the mutual repulsion of the magnetic field produced by element **1050)** and those (not shown) in the magnetic field produced by element **105**(*i*) results in field lines in the area around the center of the circle defined by magnet **101** that when seen from above are parallel and spaced uniform distances apart.

Of course, the magnetic field produced by magnet **101** actually also runs through the space above and below the surface defined by magnet **101**, as shown in side view **109**. The field lines representing the magnetic field produced by magnet **101** have the curves shown at **111** when viewed from the side. Again, only ½ of the side view is shown; the portion of the field above the surface is symmetrical to the portion below.

Using Sets of Magnets **101** to Generate Magnetic Fields: FIGS. **11** and **12**

FIG. **11** shows an arrangement **1101** of two magnets **101** in which the magnets **101** define parallel planes and the circles defined by the cores are centered on a line which is perpendicular to the parallel planes. When the magnetic field produced by a single magnet **101** is looked at in the context of arrangement **1101**, it will be immediately seen that the magnetic field in the volume between the two magnets must be the resultant of the magnetic field produced in the volume by each of the magnets **101**. As shown, corresponding magnetic elements **105** of each of the magnets **101** are on lines perpendicular to the planes defined by the magnets and are oriented in the same way. Thus, the corresponding poles of the magnets **101** are also on lines perpendicular to the planes. That of course means that the magnetic fields generated in the space between the magnets **101** repel each other. The effect of this repulsion is shown in FIG. **12**, which is a side view of arrangement **1101**. Because magnetic field **1203** is the resultant of the magnetic fields produced between the magnets **101**, and because the two magnetic fields repel each other, the field lines in magnetic field **1207** are flattened compared with the lines shown at **111** in FIG. **1**. Again, the portion of magnetic field **1203** below line **1205** is symmetrical to the portion **1207** above line **1205** and is not shown.

As is immediately apparent from FIG. **12**, arrangement **1101** may consist of any number of magnets **101** arranged on parallel planes in the same fashion as magnet **101(1)** and **101(2)**. Such arrangements are useful for manipulating magnetic fields in long vessels such as pipes. In the following, magnets of type **101** that have identical cores and arrangements of elements **105** will be termed congruent magnets **101**; those that have the same arrangement of elements **105** on the core but are of a different size will be termed similar magnets **101**.

Many versions of arrangement **101** may be constructed. For example, core **103** may have more than two elements **105**. Particularly useful configurations in this regard employ pairs of elements **105** on opposing sides of the core. If the elements are electromagnets, changing the direction and amounts of power to the elements permits creation of fields having many different configurations, and if the changes are sequenced properly, the fields may be made to rotate. The cores may define many shapes. Closed curves are useful and polygons with parallel sides are particularly useful. While planar magnets **101** are simple and useful, the magnets **101** may define non-planar surfaces. The distances between the magnets **101** may also be varied as the application requires.

Helmholtz Core Arrangements: FIGS. **11** and **12**

A particularly effective version of arrangement **1101** is the Helmholtz core arrangement. As shown in FIG. **11**, in a Helmholtz core arrangement, congruent magnets **101** are arranged in parallel planes with corresponding elements **105** being on lines perpendicular to the parallel planes and the distance between the planes being that of the coils in a Helmholtz coil, that is, the distance between magnets **101** is approximately ½ the diameter of the rings. Magnetic field **1207** shown in FIG. **12** is generated by such a Helmholtz core arrangement. The Helmholtz geometry produces a uniform field as does a standard Helmholtz coil, but the uniform field is produced by the repulsive interaction of the fields generated by the magnets **101**. The uniform field is in the center of the volume defined by the magnets **101** and is parallel to the planes of the magnets **101**. Again, more than 2 magnets **101** may be used to produce a uniform magnetic field of any length. In such an arrangement, termed a picket fence arrangement herein, each pair of adjacent magnets in the set of magnets has the Helmholtz core arrangement. To produce the uniform field, the fields produced by the magnets that are not at the ends of the picket fence arrangement should have a magnitude 25% less than those produced by the magnets at the ends of the arrangement.

Even in simple Helmholtz core arrangement **1101**, the use of windings for magnetic elements **105** permits some manipulation of the uniform magnetic field. By varying the current in the coils, the strength of magnetic field **1203** may be varied, and by reversing the current direction in the coils **1107**, the polarity of the magnetic field may be reversed. However, even in this arrangement, if separate power supplies are provided to the coils which make up the corresponding magnetic elements **105**, so that elements **105(1)(1** and **2)** and elements **105(2)(1** and **2)** receive differing amounts of power, a magnetic field with a vertical gradient may be established between magnets **101(1)** and **(2)**. As the number of opposing pairs of coils on magnet **1103** increases, the number of possible manipulations increases. For example, by adding another opposing pair of coils on each magnet **101** at 90° to the first pair, the directions and magnitudes of the power provided to the coils can be sequenced in a fashion which causes magnetic field **1203** to rotate smoothly around the line upon which the magnets **101** are centered. The number of possible manipulations can be further increased by providing separate power supplies for the coils and by increasing the number of coils.

Theory of the Helmholtz Core Arrangement

A useful way of thinking about the Helmholtz core arrangement is the following: the magnetic field lines of the magnetic field generated by magnet **101** within the circle defined by core **103** define field surfaces that are perpendicular to the plane of the magnet. Because of the effects of repulsion, as the poles of **104** and **106** of magnet **101** are approached, the surfaces become increasingly planar and are increasingly at uniform distances from each other, as seen at **107** in FIG. **1**. Thus, there is an area on either side of a line drawn between north pole **104** and south pole **106** where the field surfaces become parallel field planes that are at equal distances from each other.

When a pair of magnets **101** are arranged as shown in FIG. **11**, the field surfaces of the magnetic fields generated by the magnets **101** are aligned with each other in the area between the magnets. Each aligned surface has field lines from both magnets **101**, and these field lines all repel each other. As a result, the field lines in the aligned surfaces become more and more parallel as the center of the space between the magnets **101** is approached, as shown at **1207** in FIG. **12**. Since the aligned surfaces also become more and more parallel as the center of the space is approached, there is an area around the center of the space in which the field lines become parallel. These parallel field lines define not only the parallel planes of FIG. **1**, but also a set of parallel planes that are parallel to magnets **101**. Each of the parallel field lines is at the intersection of a plane that is perpendicular to the magnets **101** and one that is parallel to it.

As indicated above, the uniform magnetic field produced by the Helmholtz core arrangement can be manipulated by adding electromagnets to the Helmholtz core arrangement and varying the magnitude and direction of the current that is provided to these electromagnets. The entire uniform magnetic field can thus be rotated around the axis of arrangement **1101**; if sufficient electromagnets are provided and the magnitude and direction of the current to the electromagnets is properly varied, the uniform field can be modified such that the planes defined by the field lines in the uniform magnetic field appear to have been tilted in a horizontal and/or vertical direction or warped in a horizontal and/or vertical direction.

A Preferred Embodiment of an Electromagnet **101**: FIG. **2**

FIG. **2** shows a presently-preferred embodiment **201** of an electromagnet **101** for use in a Helmholtz core arrangement. Electromagnet **201** is designed to be retrofitted to a MERIE vessel of the type described above in which four electromagnetic coils are attached to the sides of the vessel. Electromagnet **201** fits around the circumference of the vessel. The four electromagnetic coils are removed and in their place are installed two electromagnets **201** which are connected to the power supplies for the four coils. The two electromagnets are separated by a vertical distance of approximately d/2, or ½ the interior distance d between opposed element sets **205** of electromagnet **201**. In an exemplary embodiment of electromagnet **201**, the distance d is approximately 15 inches. The portion of the volume between the magnets **201** in which the field is highly uniform is centered on the vertical axis of the Helmholtz core arrangement and the plane midway between the magnets **201**. The highly uniform area includes 50% of the horizontal distance d and 20% of the vertical distance d/2. Vertical displacements of the electromagnets **201** of 1 inch above and or below the distance d/2 of 7½ inches had no significant effect on the uniformity of the magnetic field.

Continuing in more detail, electromagnet **203** includes a ferrous core **203** which is shaped to fit within the form constraints imposed by the MERIE vessel being retrofitted. In electromagnet **201**, the core consists of low-carbon steel bars connected by low-carbon steel cornerpieces **204**. Wound around each bar is an element set **205** consisting of four coil elements **207**. In the preferred embodiment, elements **207(1)** and **(4)** are identical and have more windings than elements **207(2)** and **(3)**, which are also identical. The purpose of the extra windings in elements **207(1)** and **(4)** is to compensate for the lack of windings on corner pieces **204**. In an ideal element set **205**, the number of windings would decrease smoothly until the center of the element set was reached and then would increase smoothly in the same fashion, but the approximation used in electromagnet **201** is sufficient for most purposes. In the preferred embodiment, elements **207(1)** and **(4)** have N windings and elements **207(2)** and **(3)** have ⅔ N windings. Indeed, if space restrictions make it necessary, an element set **205** for producing a rotating uniform field may consist only of element **207(1)** and **207(4)**. Of course, the smaller number of elements reduces the extent to which the magnetic field can be manipulated. The manner in which elements **207** are connected to power supplies depends on the kind of magnetic field that is desired in an apparatus **101** made using electromagnets **201**.

As may be seen from FIG. **2**, element sets **205** and the bars they are wound on form a polygon (in this case, a square) around the circumference of the vessel, with the corner pieces **204** providing the corners of the polygon. The polygon may have any useful number of sides. If the fields produced by a set of electromagnets like electromagnet **201** are intended to rotate, the polygons must have opposing sides that are substantially parallel. The shapes and cross section of the corner pieces and the cross section of the bars are not critical. FIG. **13** shows two possible core cross sections. Circular cross section **1301** is preferred, but space constraints or constraints resulting from the environment into which an electromagnet **201** is retrofitted may require a rectangular cross section like that shown at **1303**. In such a cross section, better contact between the windings and the core is possible when the sides of the rectangular core are convex, as shown at **1305**, and the corners are rounded, as shown at **1307**. Good contact between the windings and the core facilitates the transfer of heat from the windings to the corner pieces via the core.

There is no requirement that core **203** be continuous; indeed, non-magnetic shims between portions of core **203** may be used for fine adjustment of the magnetic fields produced by electromagnet **201**, as shown in FIG. **14**. There, shims **1405** are used in a version **1401** of electromagnet **201** with square corner pieces **1403**. A shim **1407** has been placed in the center of each of the magnet's bars **1405**. The effect of the shims of FIG. **14** in a rotating magnetic field when the cores are saturated is to preferentially inhibit the strength of the field generated by a Helmholtz core arrangement of the magnets **1401** in one direction with regard to the field generated at 45° when the field is rotated. Preferentially inhibiting the field's strength in this manner may be used to correct at least partially for inevitable air gap field differences caused by saturation effects at 0° and 45°. Shims can also be used for field correction in situations where saturation and/or rotation are not involved. The magnetic field may also be adjusted by altering the shapes of the core and corner pieces. Examples of problems that can be dealt with by these fine adjustments include less than ideal distances between the electromagnets **201**, less than ideal element locations, or saturation effects in the core.

FIG. **15** shows a Helmholtz core arrangement **1501** made with two electromagnets **1503** which form squares with square corner pieces. The dimensions of Helmholtz core arrangement **1501** are given in terms of the length L of the bar upon which the elements **1505** and **1507** are wound.

The distance between the electromagnets **1503** is thus approximately L/2 and each element **1505** or **1507** has a length of L/4. Element **1505** has n turns and element **1507** has ⅔ n turns. As shown at **1509**, the bar has a circular cross section and the relationship between the diameter d of the circular cross section and the length L is such that d/L is approximately equal to 0.1 where maximum field strength of 100 Gauss is desired.

Examples of Magnetic Fields Generated Using an Apparatus **101** with Two Electromagnets **201**: FIGS. **3–9**

FIGS. **3–9** show how the uniform magnetic field generated by a simple Helmholtz core arrangement can be further manipulated by varying the magnitudes and directions of the currents flowing through the elements **207**. The figures show the magnetic field generated in a Helmholtz core arrangement of two electromagnets **201** at position **1205** midway between the electromagnets with various combinations of magnitude and direction of current to the elements **207**. In each of these figures, the magnetic field is shown by means of an array of freely rotating magnetic needles **303** which is mounted on a card that occupies position **1205**. Each figure also includes a schematic representation of electromagnet **201** in which element set **205(1)** is labeled N, set **205(2)** is labeled E, and so on. Elements **207** are shown as square boxes numbered **1–4**, with box **1** corresponding to element **207(1)**, box **2** to element **207(2)**, and so on. The heavy arrows **305** above the element sets **205** show the direction of the magnetic field in the elements making up the set. Thus, the magnetic field in elements **207(1)** and **(2)** of element set **205(1)** has the opposite direction from that in elements **207(3)** and **(4)**. The direction of the magnetic field produced by an element is of course determined by the direction in which the current flows through the element. What elements have current flowing through them and the relative strengths of the magnetic fields produced by the elements that have current can be seen from table **307**, which specifies the ampere turns used in each element to produce the magnetic field shown at **303**. Thus, in the case of FIG. **3**, the concave magnetic field **301** shown by the needles is produced by providing 1722 ampere turns to elements **207 2** and **4** in each of the E and W element sets **205** in the direction required by the arrows **305** for those elements and 3366, 2417, 2417, and 3366 ampere turns to elements **207(1)–(4)** respectively of element sets **207 1** and **3** in the directions required by the arrows **305** for those elements in both of the magnets **201(1)** and **(2)**.

Continuing in more detail about individual FIGS. **3–8**,

FIG. **3** shows how a concave field **301** may be produced as shown at **303** with power supply connections to the elements **207** that produce the ampere turns indicated at **307**.

FIG. **4** shows how a convex field **401** may be produced as shown at **403** with power supply connections to the elements **207** that produce the ampere turns indicated at **407**.

FIG. **5** shows how a SW–NE oriented fan field **501** may be produced as shown at **503** with power supply connections to the elements **207** that produce the ampere turns indicated at **507**.

FIG. **6** shows how a quad field **601** may be produced as shown at **603** with power supply connections to the elements **207** that produce the ampere turns indicated at **607**.

FIG. **7** shows how an N–S oriented fan field **701** may be produced as shown at **703** with power supply connections to the elements **207** that produce the ampere turns indicated at **707**.

FIG. **8** shows how a uniform field **801** may be produced as shown at **803** with power supply connections to the elements **207** that produce the ampere turns indicated at **807**. Of course, any of the above fields may be rotated by sequencing the amount and direction of power provided to each of the element sets **205** and vertical gradients may be introduced in any of the fields by providing differing amounts of power to corresponding elements in upper magnet **201(1)** and lower magnet **201(2)**.

Retrofitting an Electromagnet **201** to an Existing MERIE Apparatus: FIG. **9**

FIG. **9** is based on figures from U.S. Pat. No. 5,809,442, Olmer, et al., Silicon dioxide deposition method using a magnetic field and both sputter deposition and plasma-enhanced CVD, issued Feb. 18, 1992. The method described in the patent is applied in the system of FIG. **9**. The system employs **5** MERIE reactors **905(1 . . . 5)** of the type shown at **905** in the configuration shown at **901**. In the center of configuration **901** is transfer chamber **903**. Each of the 5 MERIE reactors has a closable port that opens onto transfer chamber **903**. A robot arm in transfer chamber **903** can transfer wafers from one MERIE reactor **905** to another. Configuration **901** thus permits performance of multiple steps of wafer processing at a single location. MERIE reactors **905** are of the type described in the Description of related art. Reactor **905** has an interior chamber **909** with a table **907** upon which a wafer may be mounted for processing. Around chamber wall **911** are arranged four coils **913(1 . . . 4)**, each of which has two horizontal and two vertical legs. Each of the coils has its own power supply. A magnetic field is generated in interior chamber **909** by activating a pair of adjacent magnets (for example, **913(1)** and **(2)**) with current flowing in one direction one power supply and the opposite pair **(913(3)** and **(4))** with another current flowing in the opposite direction form another power supply. By sequencing the manner and direction in which power is provided to the coils, the magnetic field can be made to rotate.

Successful retrofitting requires that the fewest possible changes be made to the system which is being upgraded. In the context of system **901**, what this means is that the retrofitting cannot disturb the arrangements used to transfer wafers among the reactors **905** and to introduce gases into the reactors and that the retrofitted reactor should be able to use the same power supplies as the original reactor. Helmholtz core arrangements of electromagnets **201** are particularly suited to dealing with the above constraints. As shown in FIG. **8**, only two power supplies are needed to produce a rotating uniform field **803**; four are typically available in a reactor **905**. Moreover, the facts that the electromagnets **201** in the Helmholtz arrangement are a good distance apart and that the surface of table **907** that holds the wafer is approximately midway between the electromagnets **201** mean that the Helmholtz core arrangement does not interfere with the closable ports or the robot arm. Finally, the square configuration of magnets **201** means that the mounting arrangements for coils **913(1 . . . 4)** may be easily adapted for mounting magnets **201**.

FIG. **10** shows details **1001** of retrofitting to a reactor **905**. A top view is shown at **1002** and a side view at **1004**. As shown at **1002**, reactor vessel **1003** has an octagonal cross section. The octagon has four long sides and four shorter sides. The coils **913** were mounted on the long sides. Side view **1004** shows one of the long sides **1005**; all that is left of the mounting arrangements for the coil **913** are tapped holes **1007(1 . . . 3)**; the other sides have similar tapped holes.

Top view **1002** shows a portion of electromagnet **201(1)** and the arrangements for mounting electromagnet **201(1)** and **(2)** on side **1005**. As set up for retrofitting, electromagnet **201** is made with a core consisting of four bars around which the coil elements **105** are wound and four corner pieces **204**. Each element set **205** is potted to make a single rectangular structure **1013**. Electromagnet **201** is assembled during retrofitting by connecting the bars with the corner pieces.

Each electromagnet **201** is supported by brackets like brackets **1009** on the long sides. The brackets are attached to the sides by screws that pass through the brackets and into tapped holes **1007**; as shown, there are three sets of tapped holes on side **1005** and a bracket corresponding to each set of holes. Brackets **1009(1)** and **(2)** support electromagnet **201(1)**, while bracket **1009(3)** supports electromagnet **201 (2)**. Similar brackets are employed to support electromagnets **201(1)** and **(2)** on the other sides. Electromagnet **201(1)** is assembled so that it sits on top of the top brackets and electromagnet **201(2)** is assembled so that it sits below the bottom brackets. A strap **1011** at each corner of the electromagnets **201** runs around the corresponding corner pieces of electromagnet **201(1)** and **(2)** and is tightened to urge the electromagnet **201(1)** against the top brackets and electromagnet **201(2)** against the bottom brackets. Depressions such as those shown at **1010** in the brackets correspond to bumps **1015** in rectangular structure **1013** and prevent slippage of the electromagnets **201** on the brackets. Once the electromagnets **201** have been mounted on reactor vessel **1003** in the manner just described; all that is required to complete the retrofitting is connecting the elements **207** to the original power supplies as required to produce the desired magnetic field.

CONCLUSION

The foregoing Detailed Description has disclosed to those skilled in the technology of building magnets how to make and use the apparatus for manipulating magnetic fields disclosed herein. The Detailed Description has further disclosed the best modes presently known to the inventor of making and using his invention. It will be immediately apparent to magnet builders that the underlying principles of the techniques disclosed herein are very general and that many different kinds of apparatus may be constructed which will produce magnetic fields according to the principles disclosed herein. It will further be apparent that the magnetic fields produced using the techniques disclosed herein have many applications in addition to the ones described herein, and that the ways in which the disclosed techniques are applied will vary from application to application. For all of these reasons, the Detailed Description is to be regarded as being in all respects exemplary and not restrictive, and the breadth of the invention disclosed here in is to be determined not from the Detailed Description, but rather from the claims as interpreted with the full breadth permitted by the patent laws.

What is claimed is:

1. Apparatus for producing a magnetic field comprising:

a first set of magnetic elements that define a first surface and produce a first magnetic field by repulsion between the fields produced by the magnetic elements, the first field extending normally to the first surface; and

a second set of magnetic elements that define a second surface and produce a second magnetic field by repulsion between the fields produced by the magnetic elements, the second field extending normally to the second surface,

the second set of magnetic elements being positioned relative to the first set of magnetic elements such that the surfaces are approximately parallel and the magnetic field is formed between the surfaces by repulsive interaction of the first and second magnetic fields.

2. The apparatus set forth in claim **1** wherein:

one or more of the magnetic elements in the first and/or second sets is an electromagnetic element; and

the magnetic field is manipulated by changing the direction and/or magnitude of the current in selected ones of the electromagnetic elements.

3. The apparatus set forth in claim **2** wherein:

Each set includes a first pair of electromagnetic elements that produces at least part of the set's magnetic field by repulsion and a second pair of electromagnetic elements that produces at least part of the set's magnetic field by repulsion; and

the magnetic field is manipulated by changing the direction and/or magnitude of the current in the corresponding pairs of electromagnetic elements such that a rotary motion is imparted to the magnetic field.

4. The apparatus set forth in claim **1** wherein:

the first and second sets of magnetic elements comprise a pair of magnetic elements, the like poles of the elements in a pair being connected by a core; and

the first and second sets of magnetic elements are positioned relative to each other such that a portion of the magnetic field is uniform.

5. The apparatus set forth in claim **4** wherein:

the two magnetic elements in each set of magnetic elements are separated in the surface by a distance D; and

the surfaces are separated by a distance of D/2.

6. The apparatus set forth in claim **4** wherein:

the first and second sets further comprise at least one additional pair of magnetic elements having like poles connected by the core;

the pairs of magnetic elements are electromagnetic elements; and

the uniform magnetic field is manipulated by changing the direction and/or magnitude of the current in the pairs of electromagnetic elements such that a rotary motion is imparted to the uniform magnetic field.

7. The apparatus set forth in claim **4** wherein:

the first and second sets further comprise further electromagnetic elements; and

the uniform field is manipulated by changing the direction and/or magnitude of the current in the further electromagnetic elements.

8. The apparatus set forth in claim **7** wherein:

the uniform field is manipulated by introducing a gradient between the surfaces.

9. The apparatus set forth in claim **4** wherein:

the uniform field is produced in a vessel.

10. The apparatus set forth in claim **9** wherein:

the uniform field determines behavior of particles in the vessel which are responsive to magnetic fields.

11. The apparatus set forth in claim **10** wherein:

The uniform field is produced in the neighborhood of a workpiece in the vessel, the workpiece being operated on by the particles.

12. The apparatus set forth in claim **1** wherein:

the magnetic field is produced in a vessel.

13. The apparatus set forth in claim **12** wherein:

the magnetic field determines behavior of particles in the vessel which are responsive to magnetic fields.

14. An electromagnet for use in apparatus for generating a resultant magnetic field, the electromagnet being planar and the apparatus including another such electromagnet, the planes of the electromagnets being approximately parallel in the apparatus and

the electromagnet comprising;

at least a first electromagnetic element and a second electromagnetic element; and

a core that connects like poles of the first and second electromagnetic elements,

the apparatus producing a first magnetic field in the electromagnet by repulsion, the first magnetic field being normal to the electromagnet's plane, and the apparatus producing a second such magnetic field in the other electromagnet, the first and second magnetic fields interacting by repulsion to produce the resultant magnetic field.

15. The electromagnet set forth in claim **14** further comprising:

one or more additional electromagnetic elements,

the apparatus manipulating the resultant magnetic field by changing the direction and/or magnitude of the current in the electromagnetic elements.

16. A kit for equipping a reactor with magnetic enhancement, the reactor having a chamber and the kit comprising:

a pair of electromagnets having the form of a polygon with parallel sides, the interior diameter of the polygon being such that the periphery of the chamber fits within the polygon and each electromagnet including a plurality of windings that are connectible to a power supply; and

mounts that mount the pair of electromagnets around the periphery of the chamber such that the distance between planes defined by the mounted elements is approximately one half the distance between parallel sides of the polygon.

17. The kit set forth in claim 16 further comprising: the power supply.

18. The kit set forth in claim 16 wherein:

the reactor is of the type that includes a plurality of electromagnets with horizontal and vertical legs mounted on the sides of the chamber and a power supply that provides power to the electromagnets;

the pair of electromagnets having the form of a polygon are adapted to be used with the power supply; and

the mounts are adapted to be used with mounting arrangements originally intended for the plurality of electromagnets with horizontal and vertical legs.

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